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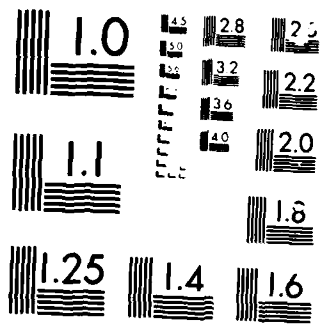

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FOREIGN TECHNOLOGY DIVISION

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A HIGH REPETITION RATE AND MODE-LOCKED PHOSPHATE GLASS LASER

by

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Abstract: High repetition rate operation of a picosecond glass laser up to 10 Hz was achieved by using a new kind of phosphate glass. The pulse duration is 24 ps, the spectral width is 0.84 Å and the total energy of the pulse train is 6 mJ.

The key to the operation of glass materials at high repetition rates lies not only in an improvement of their thermal conductivity, but also in an avoidance or elimination of the undesired optical pumping induced thermal effects, such as the optical path change due to change in the index of refraction with temperature, $\frac{dn}{dt}$ and the linear expansion coefficient, α. For silicate glass, both $\frac{dn}{dt}$ and α are positive. The new-type of phosphate glass adopted in our laboratory exhibits negative $\frac{dn}{dt}$ and positive α behavior, so that changes in the optical path resulting from both of them can be compensated by each other. As a result, such a change can reach a minimum value each time when light travels back and forth in a laser cavity.

The relation between change in the total optical path and temperature is

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$$\Delta p(r) = l\frac{dn}{dt}\Delta T(r) + l(n-1)\alpha\Delta T(r)$$
$$= Wl\Delta T(r) \quad (1)$$

where $\alpha = \frac{1}{l}\frac{dl}{dt}$, r is the distance from the center of the rod, and the thermo-optical coefficient, $W = \frac{dn}{dt} + (n-1)\alpha$.

When $\frac{dn}{dt}$ and α have different signs, $\Delta p(r)$ decreases dramatically. This is the reason why glass lasers can be operated at high repetition rates without the optical pumping induced thermal effect.

Table 1 lists the properties of the two phosphate glasses used in this investigation. It is shown from the table that both glasses have negative $\frac{dn}{dt}$ values. Since W values for these two glasses are $8.6 \times 10^{-7}/^{\circ}C$ and $4 \times 10^{-7}/^{\circ}C$, respectively, $\Delta p(r)$ in eqn. (1) almost tends toward zero.

For a satisfactory laser operation to occur at repetition rates, it is necessary to design an optimum thermostable cavity. We discussed this kind of cavity in a mode-locked laser,[1] specially under the general conditions with $a \neq 0$, where a is the distance between the center of the rod and the output lens. Change in the stability of the laser output light beam due to a small change in the focal length of the inner lens depends on the derivative of the facula size, W_1 with respect to the focal length, f, $\frac{dW_1}{W_1}/\frac{df}{f}$. When the G factor of the resonance cavity satisfies

$$G_1 = \frac{G_2}{2G_2^2 - 2\beta G_2 - \beta^2} \quad (2)$$

then $\frac{dW_1}{W_1}/\frac{df}{f} \rightarrow 0$, where subscripts 1 and 2 refer to the quantity of the output lead and that of the back surface, respectively. The facula sizes on lens 1, lens 2, and the laser rod are

$$W_1^2 = \left(\frac{\lambda L}{\pi}\right)\frac{2G_2^2 - 2\beta G_2 + \beta^2}{G_2 + \beta} \quad (3)$$

$$W_2^2 = \left(\frac{\lambda L}{\pi}\right)\frac{1}{G_2 - \beta} \quad (4)$$

Table 1. Properties of the Phosphate Glasses

参 数 - 1	N_{21}	N_{24}
非线性折射率 - 2 $n_2(10^{-13}\,esu)$	1.3 ± 0.1	1.06 ± 0.1
发射截面 - 3 $\sigma(10^{-20}$ 厘米$^2)$ 4	3.21	3.76
热膨胀 - 5 $\alpha(10^{-7}/°C)$	120.2	136.3
折射率的温度变化 - 6 $\frac{dn}{dt}(10^{-7}/°C)$	−59.3	−68.5
热光系数 7 $W(10^{-7}/°C)$	8.6	4
折射率 - 8 $n_{1.064}$ 微米 - 9	1.564	1.532
激光波长 - 10 λ(微米) - 9	1.064	1.054
荧光寿命 - 11 τ(微秒) - 12	320	280

1-parameter; 2-non-linear index of refraction; 3-emission cross section; 4-cm^2; 5-thermal expansion coefficient; 6-variation of index of refraction with temperature; 7-thermo-optical coefficient; 8-index of refraction; 9-μm; 10-wave length of laser; 11-fluoresence lifetime; and 12-microsecond.

and [illegible]

$$\times \frac{[2G_2^2-3\beta G_2+\beta^2]^2}{(1+\beta^2)(G_2+\beta)[2G_2-2\beta G_2+\beta^2]} \qquad (5)$$

where $\beta=\frac{a}{b}$, and a and b are the distance between the inner lens and the front cavity lens 1 and that between the inner lens and back cavity lens 2, respectively. When the disposition of the parts in the cavity changes, i.e., $\beta=\frac{a}{b}$ changes, the thermostable state of the cavity also changes. Fig. 1 presents the G_1G_2 stability curve for the most insensitive cavity of the laser rod thermal lens with

different values of β parameter. According to the practical dimensions of the optical elements now available, we selected $\beta=1/3$ and calculated the facula size, W_1 as a function of thermal focal length, f, as shown in Fig. 2. It can be easily inferred from this figure that when f reaches 1.5m, the cavity is deviated from the thermostable region and with $f \leq 1.1$m, the cavity is in the unstable region. Changes in the thermal focal length with pulse repetition

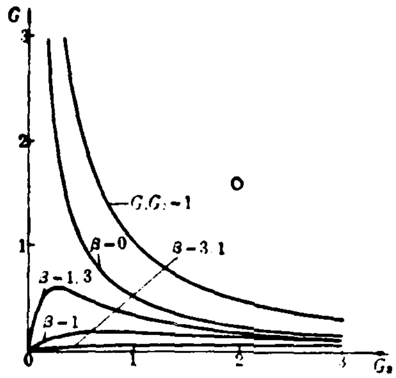

Fig. 1. The G_1G_2 stability curves of the thermally insensitive cavity

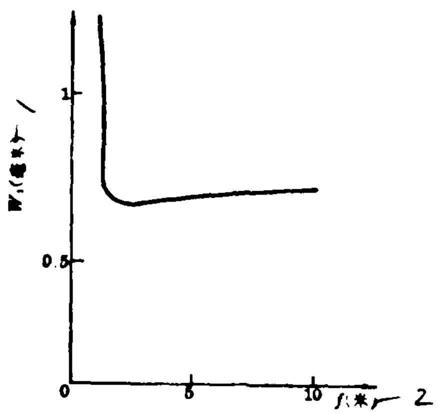

Fig. 2. Variation of the facula size, W_1 with thermal focal length. Ordinate: facula size; and abscissa: repetition rate. 1-mm; and 2-m.

rate were measured for phosphate glass N_{21}, a silicate glass and Nd:YAG. The results are shown in Fig. 3. Below the dot line, the cavity is within the unstable region. It appears that Nd:YAG can be operated at tens Hz[1] the phosphate glass at frequencies higher than 10 Hz, and the silicate glass only at frequencies lower than 5 Hz. In cases where the silicate glass is operated at 5 Hz, the cavity is already within the unstable region.

The active-passive locking mode was adopted to the laser which had a 1.5m long cavity consisting of a 7m complete reflection concave mirror and a tapered plate mirror with R=88%. A 1mm thick dye cell was connected directly to the concave mirror. The dye is pentamethyldyne dissolved in 1,2-ethyl di-chloride. The back and forth transmissivity of small signals is 0.84; the rod dimension, 6mm×100mm; the total width of the pulse train at the half peak height, 150 nanosecond (Fig. 4), the total output energy of the

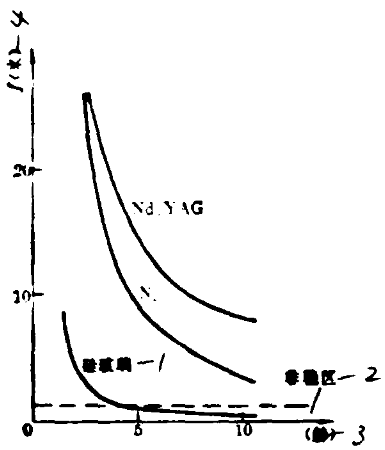

Fig. 3. Changes in the thermal focal length with pulse repetition rate for Nd:TAG, N_{21} and a silicate glass. Ordinate: focal length and abscissa: repetition rate. 1-silicate glass; 2-unstable region; 3-Hz; and 4-m.

train, 6 mJ. The pulse width was measured using double-photon fluorometry. Fig. 5 shows the densimeter scanning curve with a pulse width of 24 ps. The spectrum was run using an 1-m grating spectrograph. Its densimeter scanning curve where

Fig. 4. The mode-locked phosphate glass pulse train oscillograph. Time scale: 50 ns/cm.

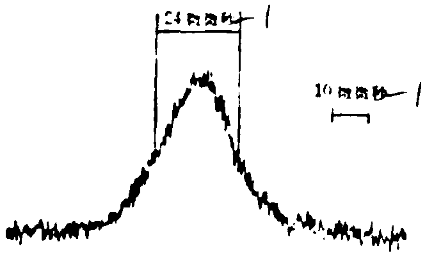

Fig. 5. The densimeter scanning curve of the double-photon fluorometry. 1-ps.

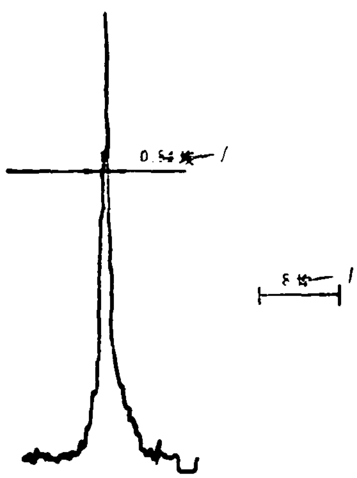

Fig. 6. The densimeter scanning curve of a spectrum picture. 1-Å.

the spectrum width is 0.84 Å is shown in Fig. 6. When the repetition rate of the laser changed from 1, 5, up to 10 Hz, the output pulse train of the oscillograph was stable and generally the output energy was also stable. This is similar to the output conditions of an Nd:YAG laser. However, the mode-locked silicate glass lasers can only be operated at 1 Hz under the same conditions. When the repetition rate reached 5 Hz, the output quickly dropped to zero. These results appear consistent with the analyses of the thermostable cavity and thermal lens.

Because of the absorption of the pumped light and the temperature gradients in the rod resulting from cooling of the rod surface, mechanical stresses were developed in the rod. Reference 2 gives the stress equation for a cylinder,

$$\sigma_r(r) = QS(r^2 - r_0^2) \tag{6}$$

$$\sigma_\phi(r) = QS(3r^2 - r_0^2) \tag{7}$$

and

$$\sigma_z(r) = 2QS(2r^2 - r_0^2) \tag{8}$$

Eqns. (6)-(8) describe the radial stress, σ_r, tangential stress, σ_ϕ and axial stress, σ_z in an isotropic rod of infinite length where

$$S = \alpha E[16K(1-\nu)]^{-1} \tag{9}$$

The Young's modulus, E, the thermal conductivity, K, and the Poisson ratio, ν are all the characteristic parameters of the material. Also, we have

$$Q = \frac{P_a}{\pi r_0^2 L} \tag{10}$$

where r_0 is the radius of the rod; L, the rod length; and P_a, the internal friction power of the rod. The stress distribution is a parabola of r. Using eqns.(6)~(8) and substituting the material's characteristic parameters, with the pump energy of 850w, stress as

a function of the radius of the phosphate glass rod was calculated, as shown in Fig. 7. These curves indicate that at the rod surface, the radial component of the stress approaches zero; at the center of the rod, all the three components are negative, so that the center is in compression; and again at the surface, both the tangential and axial components are positive and the surface is in tension. The maximum stress appeared at the center and at the surface of the rod. With an increase in the power dissipation in the rod, tension at the surface increased. Addition of vectors σ_ϕ and σ_Z in eqns. (7) and (8) results in σ_{max}:

$$\sigma_{max} = \frac{\sqrt{2}\,\alpha E}{8\pi K(1-\nu)}\,\frac{P_o}{L} \qquad (11)$$

We measured the dissipation energy which caused rupture of the rod,

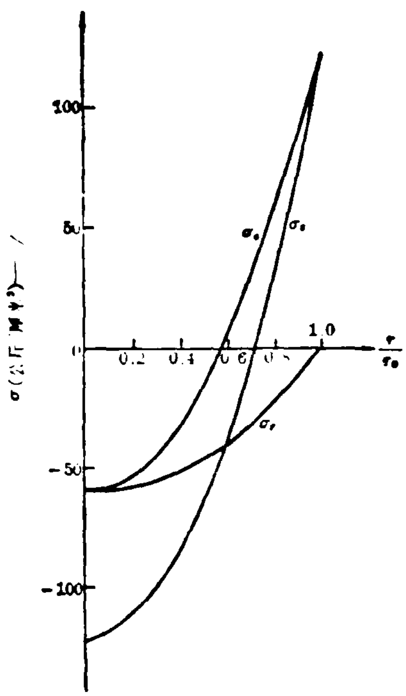

Fig. 7. Distribution of the internal stress of a phosphate glass rod. Ordinate: stress; and abscissa: normalized radius. 1-kg/cm².

and found that the thermal expansion happened when N_{21} was 850w and N_{24}, 990w. From this, the tensile strengths were estimated as 180 kg/cm^2 for N_{21} and 230 kg/cm^2 for N_{24}. In fact, the actual rupture strength of a laser rod strongly depends on rod surface finish conditions. It was reported by the Soviets[3] that the measured rupture strength of a phosphate glass is 205 kg/cm^2, expansion coefficient, $99\times10^{-7}\,°C^{-1}$ with the same tensile strength as given in this paper.

The actual operation energy of the mode-locked phosphate glass lasers is 54 Joules. The thermal expansion data show the possibilities of operating these lasers at over 10 Hz, with the major obstacles being thermal expansion. A well polished rod surface has no imperfactions and no stress, and can, therefore, have an increased thermal loading.

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